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Broca's Area and the Hierarchical Organization of Human Behavior

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Summary

The prefrontal cortex subserves executive control, i.e., the organization of action or thought in relation to internal goals. This brain region hosts a system of executive processes extending from premotor to the most anterior prefrontal regions that governs the temporal organization of behavior. Little is known, however, about the prefrontal executive system involved in the hierarchical organization of behavior. Here, we show using magnetic resonance imaging in humans that the posterior portion of the prefrontal cortex, including Broca's area and its homolog in the right hemisphere, contains a system of executive processes that control start and end states and the nesting of functional segments that combine in hierarchically organized action plans. Our results indicate that Broca's area and its right homolog process hierarchically structured behaviors regardless of their temporal organization, suggesting a fundamental segregation between prefrontal executive systems involved in the hierarchical and temporal organization of goal-directed behaviors.

Introduction

Human behavior is often guided by internal states and goals. This ability to select and coordinate actions or thoughts in relation to internal goals is referred to as executive control and is a cardinal function of the prefrontal cortex (Koechlin et al., 2003; Miller and Cohen, 2001). A basic dimension of executive control is the organization of behavior across time and the processing of crosstemporal contingencies between past, present, and expected future events for selecting appropriate action (Fuster, 1989). As revealed by previous studies (Braver et al., 2003; Fuster, 2001; Koechlin et al., 2003), the temporal dimension of executive control is processed in the lateral prefrontal cortex by a top-down control system of executive processes extending from premotor to the most anterior prefrontal regions. In this system, more anterior regions integrate temporally more dispersed information for selecting appropriate behaviors at each time. This prefrontal system, however, is not involved in the precise timing of motor acts underlying the execution of motor sequences, a distinct function associated with medial regions of the premotor cortex including the supplementary motor area complex (Kennerley et al., 2004; Tanji, 2001).

Another basic dimension of executive control is the hierarchical organization of behavior. In this dimension, appropriate actions are selected as subordinate elements that compose ongoing structured action plans rather than from occurrences of temporally distant events. In other words, action selection may result from processing the hierarchical structure of action plans evoked by external events rather than processing crosstemporal contingencies between events. Little is known about the prefrontal executive system subserving action selection based on hierarchical structures of behavioral plans. We reasoned that this system should be confined to the posterior portion of the lateral prefrontal cortex, including Broca's area and its homolog in the right hemisphere, on the basis of the following assumptions: first, this prefrontal region is specifically engaged in executive control involving temporally concomitant events (Braver et al., 2003; Koechlin et al., 2003). Second, Broca's area is thought to play a critical role in processing hierarchical structures in human language (Dominey et al., 2003; Musso et al., 2003). Third, anterior prefrontal regions located in front of Broca's area and its right homolog are engaged regardless of the hierarchical complexity of action plans (Koechlin et al., 2000, 2003). Thus, we hypothesized that Broca's area and its right homolog (both referred to as BCA for simplicity) implement a specialized executive system governing action selection in hierarchically structured action plans, regardless of their temporal structure.

This hypothesis makes two specific predictions. First, the hypothesis predicts that BCA regions are functionally organized from premotor to anterior BCA regions as a hierarchy of representations controlling action selection across different levels of action plans. More anterior regions are involved in processing hierarchically higher levels. This idea is consistent with the view that processing hierarchically higher behavioral plans engages more anterior frontal regions (Fuster, 1989) and top-down control is exerted from anterior to posterior frontal regions (Koechlin et al., 2003). The second prediction is that BCA regions process hierarchical relations rather than crosstemporal contingencies between the elements comprising action plans. Hierarchical relations are important for action selection only when two successive actions involve selection or inhibition of hierarchically higher representations of an action, i.e., when the first action corresponds to the termination of an ongoing action segment and/or the subsequent action to the initiation of a new action segment. Thus, our hypothesis predicts that BCA regions should show phasic activation at the boundaries of action segments that constitute a hierarchical action plan, which is opposite to the idea of sustained activations during action execution.

To examine those predictions, we assumed as previously suggested (Koechlin et al., 2002) and in agreement

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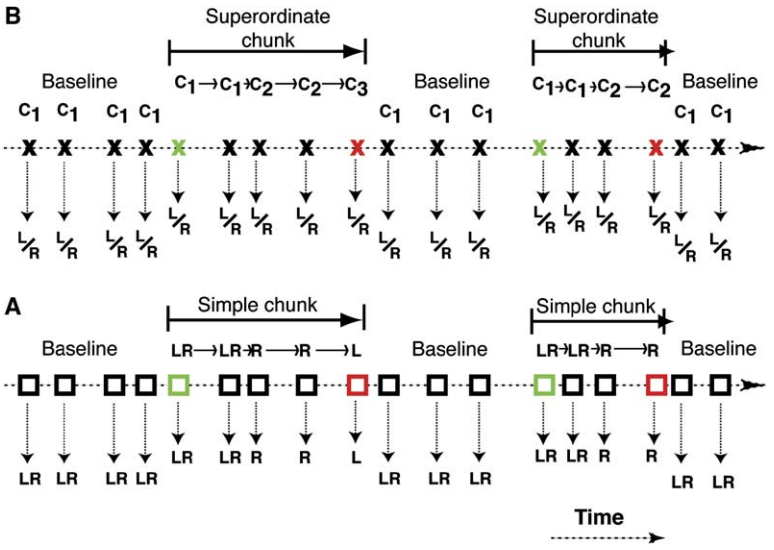

Figure 1. Experimental Protocol

The figure represents truncated series of trials in the simple (A) and superordinate (B) condition. Vertical arrows indicate the motor response that subjects made in each trial. In the simple condition (A), stimuli were a single square symbol, and subjects responded by pressing either the left (L), right (R), or both (LR) response buttons. In the superordinate condition (B), stimuli were pseudorandomly chosen letters A, B, or C (represented by the symbol X). In each trial, subjects performed a categorization task (represented above stimuli by c_1, c_2, c_3), pressing either the left or right button (L/R) in response to each stimulus X. Horizontal arrows represent the transitions between the motor acts (A) and categorization tasks (B) comprising the simple and superordinate chunk, respectively. Colors of stimuli served as start and stop cues (green and red, respectively), triggering initiation and termination of chunk trials. Black color represents other randomly chosen colors (blue and yellow) that served as distractors. Left, endogenous termination, i.e., stop cues appeared at the end of learned sequences. Right, examples of exogenous termination, i.e., stop cues appeared before the end of learned sequences. See Experimental Procedures for additional information.

with computational models of action planning (Dehaene and Changeux, 1997) that action plans can be composed of at least three nested hierarchical levels: the level of *single motor acts* or single sensorimotor associations; the level of *simple action chunks*, including either sequences of single motor acts or sensorimotor mappings; finally, the level of *superordinate action chunks* composed of simple action chunks, i.e., consistent sets or sequences of simple action chunks. For example, a sequence of categorization tasks, like sorting a deck of playing cards first by color, then by suit, then by rank, forms a sequence of distinct sensorimotor mappings, i.e., a superordinate chunk. Note that these hierarchical levels are defined regardless of the temporal structure of the action plans, because each level includes either sequential or parallel sets of subordinate representations of action.

Thus, according to our hypotheses, premotor regions will be involved in selecting single motor acts or single sensorimotor associations. Posterior BCA regions (typically pars opercularis, BA 44) will be involved in selecting/inhibiting simple action chunks through top-down interactions that initiate and terminate successive selections of simple chunk components occurring in the premotor regions (i.e., single motor acts or sensorimotor associations). Finally, anterior BCA regions (typically pars triangularis, Brodman's area 45) will be involved in selecting/inhibiting superordinate action chunks through top-down interactions that initiate and terminate successive selections of superordinate chunk components occurring in the posterior BCA regions (i.e., simple action chunks; see Figure 7).

This model predicts that anterior BCA regions exhibit phasic activations at boundaries of superordinate chunks, while posterior BCA regions exhibit phasic activations at simple chunk boundaries. Premotor regions should exhibit phasic activations, whenever motor acts that are parts of ongoing simple action chunks are selected or occur in response to stimuli. Furthermore, the different levels are nested together, so that boundaries of superordinate action chunks correspond to boundaries of simple action chunks forming their start and end states. Similarly, boundaries of simple action chunks correspond to initial and terminal motor acts. Consequently, because of top-down interactions, boundaries of superordinate action chunks will be associated with phasic activations in anterior, posterior BCA, and premotor regions, while boundaries of simple chunks will be associated with phasic activations in posterior BCA and premotor regions only. In contrast, selection of motor acts will only involve premotor regions. Behavioral reaction times should also reflect this sequential engagement and hence be larger at boundaries than for intermediate steps of superordinate chunks and larger at boundaries than for intermediate steps of simple chunks (Sternberg, 1969).

Results

Experimental Protocol

Using fast event-related functional magnetic resonance imaging (fMRI), we tested our predictions by scanning 16 healthy human subjects in a behavioral experiment including two conditions and designed to vary the hierarchical level of action plans independently of their temporal structure (see Figure 1 and Experimental Procedures for details). In both conditions, subjects performed series of motor responses by pressing left or right hand-held response buttons. Button presses were triggered by visual stimuli presented at random times.

In the *simple* condition, subjects executed a prelearned sequence of button presses, i.e., a simple chunk that was repeated in alternation with a baseline task consisting of a repeated single motor response (referred to as the motor baseline). In the *superordinate* condition, subjects made button presses corresponding to a prelearned sequence of categorization tasks, i.e.,

a superordinate chunk. In response to each stimulus, subjects pressed the left or right button appropriate to the current categorization task before inferring the next categorization task of the learned sequence in order to respond correctly to the next stimulus. Again, the sequence of categorization tasks was alternated with a baseline of responses corresponding to a repeated single categorization task (referred to as the chunk baseline).

Switching between baseline and chunk performance was signaled for both simple and superordinate tasks by additional, randomly presented visual cues indicating when to initiate and terminate action chunks. Thus, in both simple and superordinate conditions, trials with start and stop cues (referred to as initiation and termination trials), corresponded to simple and superordinate chunk boundaries, respectively. In contrast, intermediate trials in the simple chunk condition corresponded to transitions between component motor acts and intermediate trials in the superordinate chunk condition corresponded to transitions between component simple chunks.

The behavioral protocol thus varied the hierarchical level and the temporal structure of action plans independently. Indeed, action plans in the two conditions were at different hierarchical levels but shared the same temporal structure because the timing of external events triggering action selection and execution (visual stimuli, start and stop cues) were set to be exactly the same in both conditions. In contrast, simple chunks in the simple condition and those forming the superordinate chunks had different temporal structures (sequence of single motor acts versus sensorimotor mappings, respectively), despite sharing the same hierarchical level.

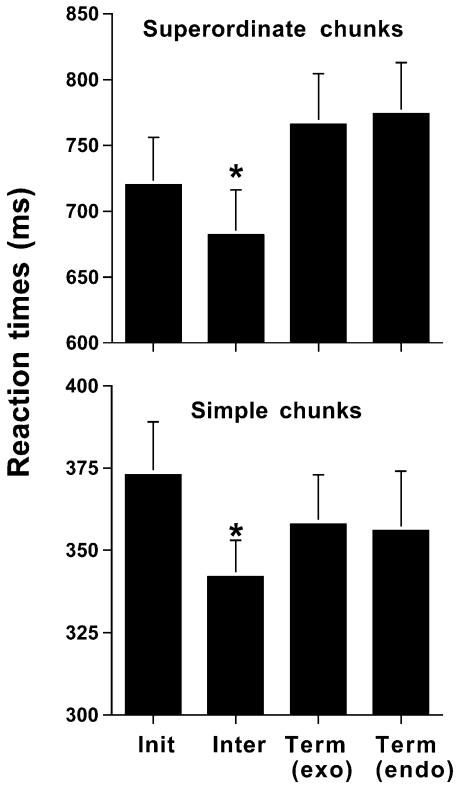

Figure 2. Behavioral Results

Reaction times to stimuli (mean ± SEM across subjects averaged over correct responses) in chunk trials. Init, initiation trials. Inter, intermediate trials occurring after start and before stop cues. Term, termination trials. Exo, exogenous; Endo, endogenous. Subject's error rates were lower than 8% in every trial type. Trials including errors were factored out in all analyses.

Behavioral Results

Behavioral results confirmed that action chunks were appropriately overlearned before the experiment so that no residual learning occurred during scanning. Mean error rates (ERs) were 2.5% (standard error—0.5%) and 4.4% (SEM—1%) during simple and superordinate chunk performance, respectively. More critically, behavioral results did not significantly vary between the first and last scanning sessions (ERs—$Fs < 1.2$, $Ps > 0.29$; reaction times—$Fs < 2.3$, $Ps > 0.15$ for both simple and superordinate chunks. See Figure S2 in Supplemental Data available with this article online), confirming the absence of learning during the experiment.

As predicted, RTs were longer in initiation and termination than intermediate trials in both simple and superordinate tasks (simple condition—both $Fs > 4.6$, $p < 0.048$, two-tailed; superordinate condition—both $Fs > 6.3$, $p < 0.025$, two-tailed; see Figure 2). No significant differences in RTs were found between termination trials occurring at the end of learned action sequences (endogenous terminations) and those occurring earlier (exogenous terminations; both $Fs < 1$; Figure 2).

fMRI Results

fMRI data from the lateral prefrontal cortex confirmed the implementation of hierarchical control in BCA regions (Figures 3 and 4; Table 1; see Experimental Procedures for details). In the simple condition, activations associated with transitions between component motor acts (i.e., increased phasic activations in intermediate trials compared to motor baseline trials) were observed in bilateral premotor regions only (green regions in Figure 3). In contrast, activations associated with initiation and termination of simple action chunks (i.e., increased phasic activations in initiation and termination compared to intermediate trials) were found in posterior BCA regions bilaterally (yellow and white regions in Figure 3).

As predicted, in the superordinate condition, activations associated with transitions between component simple chunks (i.e., increased phasic activations in intermediate trials compared to chunk baseline trials) were found in virtually the same posterior BCA regions as those identified above (yellow and orange regions in Figure 3). In contrast, activations associated with initiation and termination of superordinate action chunks (i.e., increased phasic activations in initiation and termination compared to intermediate trials), were observed in anterior BCA regions bilaterally (red regions in Figure 3). Cytoarchitectonic maximum probability maps of Broca's area and its right homolog (Amunts et al., 1999; Eickhoff et al., 2005) indicate that the posterior and anterior BCA activations found were located in Brodman's area 44 and 45, respectively (see Figure S3 and Table S1).

In the frontal cortex, only the anterior supplementary motor area (pre-SMA) and the left and right anterior

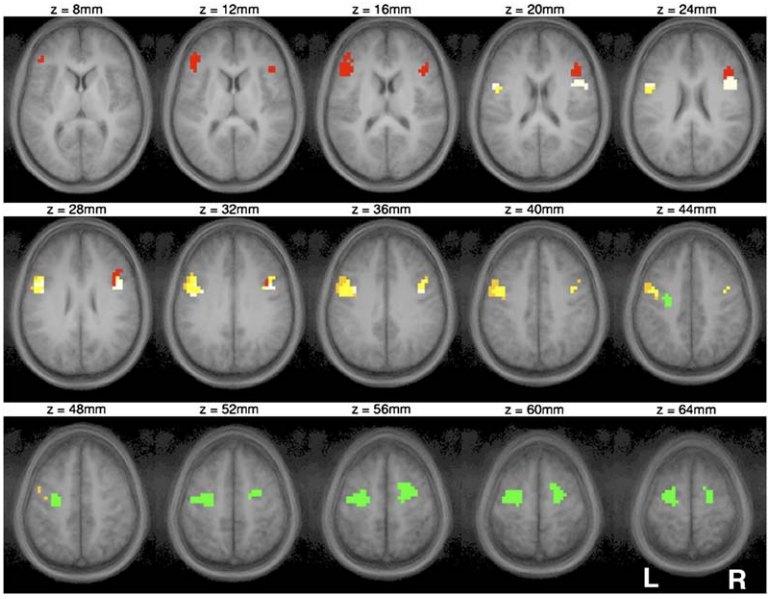

Figure 3. Topography of Lateral Frontal Activations

Green: regions activated in transitions between single motor acts. Yellow: regions jointly activated in initiation/termination of simple chunks and in transitions between simple chunks. White: regions activated in initiation/termination of simple chunks only. Orange: regions activated in transitions between simple chunks only. Red, regions activated in initiation/termination of superordinate chunks only. Activations are superimposed on anatomical axial slices averaged across subjects (neurological convention) and indexed by the vertical Talairach coordinate (z). Only lateral frontal activations are shown.

insula also showed phasic activations, exhibiting the same phasic response profile as posterior BCA regions (Figures 5 and 6). In these medial frontal and insular cortices, however, there was no evidence for functional segregations between simple and superordinate chunks. In posterior brain regions, phasic activations were found only in the left and right inferior parietal cortex (BA 40) during simple and superordinate chunk compared to baseline trials, with again no evidence to support functional segregation between the two.

Finally, sustained activations during simple and superordinate chunk compared to baseline trials were found in left and right inferior parietal regions (BA 40) only. Sustained activations were also found in both the insula and pre-SMA during simple chunk trials only (Figure 6).

Factorial Analyses

Additional analyses of variance were performed to further assess effects of critical theoretical significance (Figure 4; see details in Experimental Procedures): we analyzed (1) effects of boundaries of simple and superordinate chunks (corresponding to increased phasic activations in initiation and termination compared to intermediate trials); (2) effects of transitions between single motor acts comprising simple chunks and between simple chunks comprising superordinate chunks (which correspond to increased activations in intermediate trials compared to baseline trials in the simple and superordinate condition, respectively).

These analyses confirmed that bilateral anterior BCA regions showed effects of boundaries in superordinate chunk trials only (simple chunk—$F = 1.4$, $p = 0.24$; superordinate chunk—$F = 33.7$, $p < 0.001$; interaction—$F = 12.0$, $p < 0.001$). No differences were observed between initiation and termination (simple chunk—$F = 2.9$, $p = 0.10$; superordinate chunk—$F < 1$) nor between endogenous and exogenous termination (simple chunk—$F = 1.4$, $p = 0.24$; superordinate chunk—$F < 1$; Figure S1). No significant effects of transitions between simple chunks and motor responses were observed ($F = 3.4$, $p = 0.07$, interaction—$F < 1$). All effects were independent of hemisphere (left versus right, all interactions $Fs < 2.0$, $Ps > 0.16$).

Bilateral posterior BCA regions, in contrast, exhibited effects of boundaries in both simple and superordinate chunk trials (both $Fs > 19.8$, $p < 0.001$; interaction—$F < 1$). No differences were observed between initiation and termination ($F = 1.5$, $p = 0.23$) nor between exogenous and endogenous termination ($F = 1.1$, $p = 0.3$; Figure S1). As predicted, there were significant effects of transitions between simple chunks ($F = 12.0$, $p < 0.001$) but not between motor responses ($F = 2.7$, $p = 0.11$). Again, all effects were independent of hemisphere (left versus right, all interactions $F < 1$).

As predicted, premotor regions showed effects of boundaries in both simple and superordinate chunk trials (both $Fs > 8.6$, $p < 0.001$; interaction—$F = 1.9$, $p = 0.17$), and effects of transitions between both simple chunks and motor responses ($F = 41.5$, $p < 0.001$; interaction—$F < 1$). Again, no difference was observed between initiation and termination ($F < 1$) nor between exogenous and endogenous termination ($F < 1$; Figure S1). All effects were independent of hemisphere (left versus right, all interactions $Fs < 1.7$, $p > 0.19$).

Finally, crossregional analyses of variances confirmed the functional dissociations described above (see Experimental Procedures for details). Effects of boundaries in simple and superordinate chunk trials differed significantly between anterior and posterior BCA regions (condition x region interaction—$F = 12.6$, $p < 0.003$). Effects of transitions between simple chunks also differed in the two regions (interaction—$F = 15.0$, $p < 0.002$), whereas the effects of transitions between motor responses differed in posterior BCA and premotor regions (interaction—$F = 5.4$, $p < 0.036$).

Discussion

We suggested that Broca's area and its right homolog implement a specialized executive system that governs action selection based on processing hierarchical

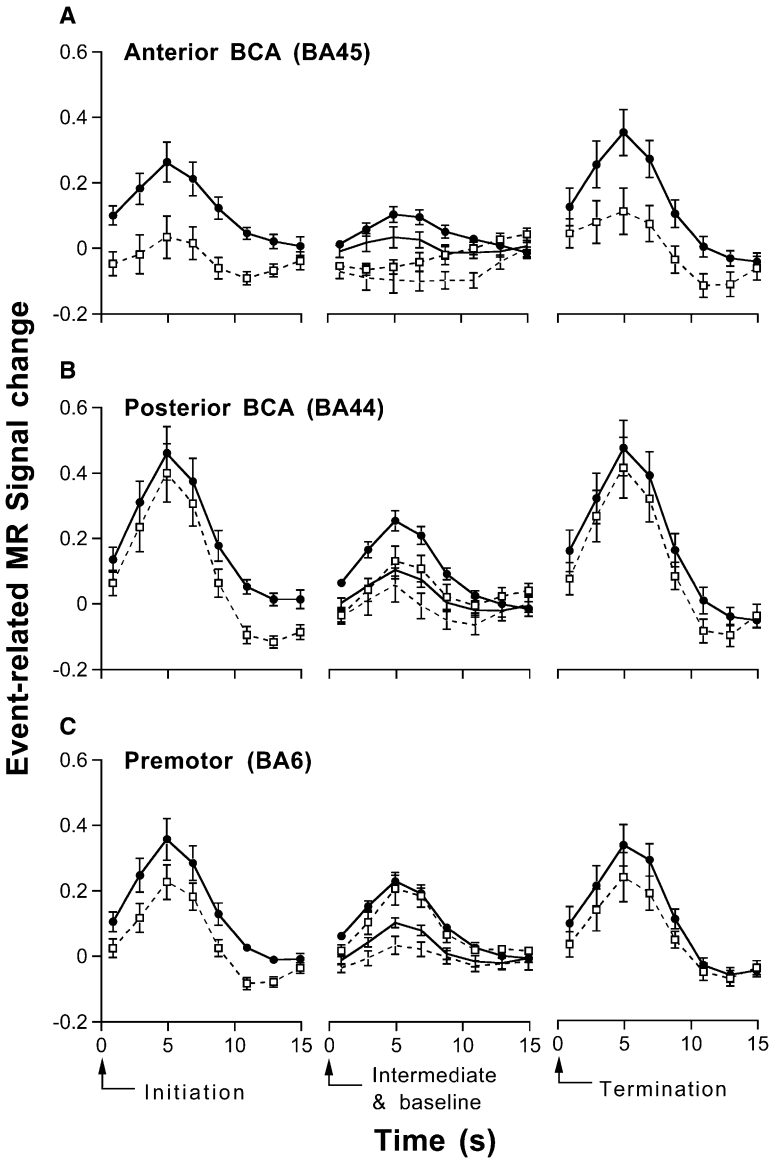

Figure 4. Time Courses of Lateral Frontal Activations

Reconstruction of event-related magnetic resonance (MR) signal changes associated with each trial type in anterior (top), posterior (middle) BCA, and lateral premotor (bottom) regions averaged over both hemispheres and subjects (error bars are standard errors across subjects). Solid lines: superordinate condition. Dashed lines: simple condition. Left, initiation trials. Middle, intermediate trials and baseline (no symbol) trials. Right, termination trials. x axis origins are stimulus onsets. For each trial type, data points are adjusted and peristimulus MR signals averaged over time bins of 2 s and obtained after subtracting the estimated contribution of other events based on parameter estimates of the multiple linear regression model. Data points are positioned on the x axis at the center of time bins (i.e., at 1 s, 3 s, 5 s, etc.). y axis origins are the averaged event-related MR signal in motor baseline trials (middle and bottom panels) and chunk baseline trials (top panel).

relations rather than crosstemporal contingencies between the elements of action plans. From this hypothesis, we proposed a simple model consisting of a hierarchy of representations extending from premotor to anterior BCA regions that controls action selection through top-down interactions across hierarchical levels of action plans. More anterior regions in this architecture process hierarchically higher levels. Our results confirm the predictions of this model. We now examine whether there are any plausible alternative interpretations that might explain the cerebral responses.

First of all, variations in motor responses, e.g., bimanual versus unimanual movements (Koeneke et al., 2004), are unlikely to explain variability of BCA activity across trials and conditions. Indeed, no differences in BCA activations were observed between initiation and termination trials in simple chunk trials, although initiation and termination trials involved bimanual and unimanual movements, respectively. Conversely, BCA activity in simple chunk trials differed between intermediate and termination trials despite the fact that all the movements were unimanual. Similarly, differences in BCA activity between intermediate and termination trials differed between simple and superordinate conditions, despite the fact that all trials included unimanual movements. Thus, BCA activity is unrelated to variation in motor responses across experimental trials and conditions.

Second, activations observed in premotor and BCA regions are unlikely to result from variable mental effort across trials. The amplitude of phasic activations in intermediate steps of superordinate chunk performance in these regions does not exceed those observed at the boundaries of simple chunk trials (Figure 4B), although the former were associated with significantly longer RTs (Figure 2). This finding is incompatible with a variable effort explanation. Similarly, despite significant variability of RTs, the amplitude of posterior BCA activations was virtually identical at the boundaries of simple and superordinate chunk trials (Figure 4B) as were the amplitude of premotor activations in

Table 1. Brain Activations in the Frontal Lobes

Brain Regions	Volume (cm^3)	Z Score Maxima (Fixed Effects) Talairach Coordinates	Z Scores	Max T Scores (Random Effects)
Regions Activated in Initiation/Termination of Superordinate Chunks Only				
L IFG BA 45	2.4	−44, 24, 16	4.59	3.77
		−48, 36, 16	4.78	
R IFG BA 45	2.4	44, 24, 20	6.41	4.99
Regions Activated in Transitions between Simple Chunks[a]				
L IFG, BA 44	6.1	−52, 12, 32	5.72	5.99
		−52, 0, 44	6.77	
R IFG, BA 44	1.0	44, 12, 32	4.06	3.24
		40, 4, 40	4.37	
L insula	3.5	−32, 16, −4	5.38	4.41
R insula	0.7	32, 16, −4	4.35	3.71
Pre-SMA	11.5	−8, 0, 60	7.56	4.91
Regions Activated in Initiation/Termination of Simple Chunks				
L IFG, BA 44	4.0	−44, 4, 36	>10	5.67
R IFG, BA 44	3.1	40, 4, 32	7.20	5.31
L insula	2.4	−44, 12, 4	5.73	3.95
R insula	3.8	44, 16, 4	6.79	5.05
Pre-SMA	9.7	−8, 8, 56	>10	4.74
Regions Activated in Transitions between Single Motor Acts*				
L PM, BA6	7.3	−28, −12, 52	7.04	5.61
R PM, BA6	3.7	24, −8, 60	5.13	5.17

Z scores and T scores are for the statistical contrasts described in the Results and Experimental Procedures.
IFG: inferior frontal gyrus. SMA: supplementary motor area. PM: premotor cortex. L: left. R: right.
[a] Excluding premotor activations reported in *.

intermediate steps of simple and superordinate chunk trials (Figure 4C, middle). Thus, phasic activations in premotor and BCA regions cannot be solely explained by variable mental effort across trial types.

Third, relational complexity, i.e., the number of independent relations that need to be processed and combined together to select appropriate motor responses (Christoff et al., 2001), is unlikely to explain the data because BCA activity was different between boundary and intermediate steps of action chunks, without any difference in relational complexity between such trials. The only difference between these trials was the distribution of relations over hierarchical levels. Similarly, the variable difficulty of retrieving or loading behavioral rules of increasing complexity cannot explain our results because there was no retrieval associated with termination and the same phasic activity was found in both initiation and termination trials.

Fourth, given the well-documented involvement of Broca's area in human language (e.g., Martin, 2003), another alternative interpretation of our results is that the BCA and especially Broca activations reflect inner speech or covert verbalization during performance of the tasks. Such an interpretation, however, does not account for differences in BCA activation between boundary and intermediate steps of both types of action chunk.

Fifth, given that anterior BCA regions receive projections from the temporal cortex (Petrides et al., 2005; Petrides and Pandya, 2002), i.e., from the ventral visual pathway involved in stimulus identification, anterior BCA activations might simply result from increased involvement of this pathway in the superordinate condition that required visual categorization. This interpretation is not supported by the data because anterior BCA activations at the boundaries of superordinate chunk trials were unassociated with activations in the temporal cortex. More generally, alternative interpretations based on differences in visual processing between conditions are unlikely to account for the functional segregation observed in BCA, because all posterior brain activations during simple and superordinate chunk compared to baseline trials were confined to the inferior parietal lobule (BA 40). This finding confirms that the experimental protocol controlled for visual processing across trials and conditions appropriately, given that in each condition all trials involved exactly the same visual processing for selection of motor responses.

Sixth, the BCA activations cannot be explained by a functional segregation between regions involved in externally versus internally guided selection of action segments (Rogers and Monsell, 1995). Indeed, in both types of action chunk, differences in BCA activation were observed between initiation/termination and intermediate trials only. However, selection of action segments were guided by external cues in exogenous termination trials only and by internal signals in all other trials (initiation, intermediate, and endogenous termination; Figure 1). Similarly, BCA activation is unlikely to result from cognitive factors such as increasing demands on perceptual attention or arousal associated with the start and stop cues (Posner and Petersen, 1990), because in response to these cues different parts of BCA were activated in the simple and superordinate condition. Moreover, posterior BCA activations were found in the absence of start and stop cues, namely in intermediate steps of superordinate chunks (Figures 3 and 4).

Finally, the functional segregation found in BCA regions was independent of the temporal structure of action chunks. Simple and superordinate chunk conditions were based on the same temporal structure but engaged distinct BCA regions. Conversely, the pattern of BCA activation was the same in processing simple action chunks with distinct temporal structures like temporal sequences of motor responses (simple condition) and sensorimotor mappings (categorization tasks in the superordinate condition).

Having ruled out alternative interpretations, we conclude that the results support our proposed model of hierarchical control in BCA regions. More specifically, anterior BCA regions show phasic activation at boundaries of superordinate chunks only, providing evidence that these regions are specifically involved in selecting or inhibiting superordinate action chunks. Compared to anterior BCA regions, posterior BCA regions additionally exhibited phasic activations at boundaries of simple chunks and in the transitions between simple chunks forming superordinate actions. Thus, posterior BCA regions are involved in selecting and inhibiting simple action chunks in response to external signals or as successive components of ongoing superordinate actions. Posterior BCA regions also showed phasic activation at boundaries of superordinate chunks. As explained above, such activations are unlikely to result from

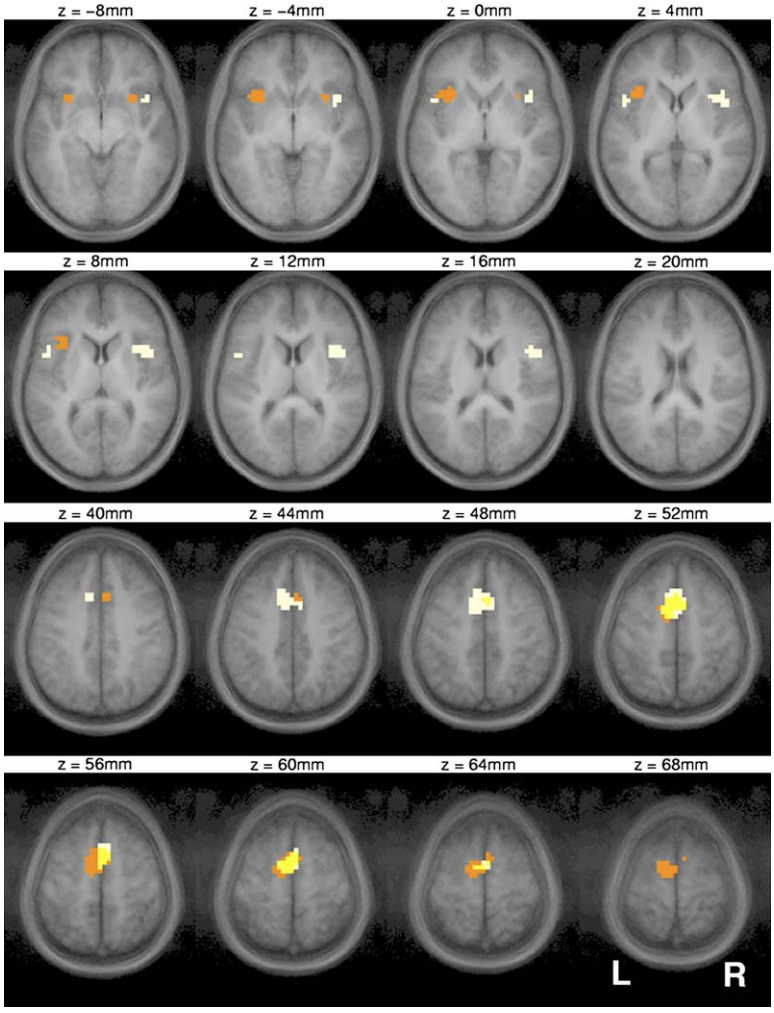

Figure 5. Topography of Insular and Pre-SMA Activations

The color code is the same as in Figure 3. Yellow: regions jointly activated in initiation/termination of simple chunks and in transitions between simple chunks. White: regions activated in initiation/termination of simple chunks only. Orange: regions activated in transitions between simple chunks only. Activations are superimposed on anatomical axial slices averaged across subjects (neurological convention) and indexed by the vertical Talairach coordinate (z). Talairach coordinates of activation peaks are provided in Table 1.

externally guided, bottom-up selection/inhibition of simple chunks in response to start and stop cues. Instead, such activations provide evidence that top-down control is exerted from anterior to posterior BCA regions and conveys trigger signals for starting and stopping successive selection of component simple chunks at the boundaries of superordinate chunks. Premotor regions showed the same activation profile as posterior BCA regions except that they showed additional phasic activations in transitions between motor responses composing simple action chunks (Figure 4). Reasoning as above, we conclude that premotor regions are involved in selecting motor acts in response to stimuli or as successive components of ongoing simple action chunks. Top-down control is exerted from posterior BCA to premotor regions for starting and stopping successive selection of component motor acts at the boundaries of simple chunks.

In summary, the results show that Broca's area and its right homolog are functionally organized as a system of top-down executive processes extending from premotor to anterior BCA regions that control action selection across hierarchical levels of action plans, ranging from single motor acts to simple and superordinate action chunks, respectively (Figure 7). In this system, more anterior regions select and inhibit hierarchically higher action plans and generate top-down trigger signals that in more posterior regions initiate and terminate the successive selection of subordinate segments that constitute those action plans. Importantly, we found that this system operates independently of the temporal structure of action plans. This finding is consistent with previous studies showing that patients with lesions of Broca's area are impaired in learning the hierarchical but not the temporal structure of sequential tasks (Dominey et al., 2003). The lack of significantly sustained BCA activations during the execution of overlearned action plans in our study indicates that these regions are not significantly involved in preparing or maintaining representations or keeping track of sequential progression of an action over time. Instead, our result suggests that the executive system implemented in BCA regions is restricted to process start and end states and to control the nesting of functional segments forming the hierarchical structure of action plans (Figure 7). This conclusion is consistent with previous electrophysiological recordings demonstrating neurons in the monkey posterior prefrontal cortex that selectively code for start and end states of behavioral sequences (Fujii and Graybiel, 2003).

In accordance with previous studies (Augustine, 1996; Kennerley et al., 2004; Sakai et al., 1998; Tanji, 2001), we

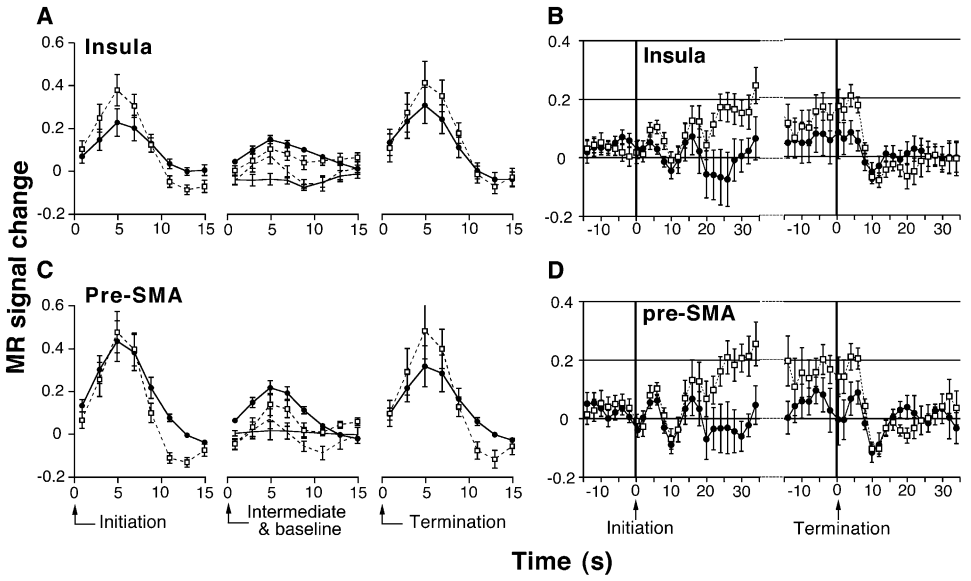

Figure 6. Phasic and Sustained Activations in the Insula and Pre-SMA

(A and C) Graphs show reconstruction of event-related magnetic resonance (MR) signals associated with each trial type. Solid lines: superordinate condition. Dashed lines: simple condition. Left, initiation trials. Middle, intermediate trials and baseline (no symbol) trials. Right, termination trials. y axis origins are the averaged event-related MR signal in motor baseline trials.

(B and D) Graphs show reconstruction of epoch-related magnetic resonance (MR) signals during simple (square, dashed lines) and superordinate (circle, solid lines) conditions. In all graphs, data points are MR signals averaged over both hemispheres and subjects (error bars indicate standard errors across subjects). x axis origins are stimulus onsets. Data points are adjusted and peristimulus MR signals averaged over time bins of 2 s and obtained after subtracting the estimated contribution of other events based on parameter estimates of the multiple linear regression model. Data points are positioned on the x axis at the center of time bins (i.e., at 1 s, 3 s, 5 s, etc.).

found evidence that managing the execution of structured action plans over time (i.e., preparing, maintaining representations, or keeping track of sequential progression of actions in structured actions plans) involve other brain regions including the inferior parietal cortex, the SMA complex, and the insula. Indeed, these regions showed sustained activation related to the temporal extension of action chunks. In the SMA complex and the insula, sustained activations were observed in the simple condition only, when subjects executed overlearned motor sequences. In agreement with previous studies (e.g., Dronkers, 1996; Kennerley et al., 2004; Tanji, 2001), such sustained activations simply reflect successive preparation of motor movements in ongoing overlearned motor sequences. Consistently, no sustained activations were found in the superordinate condition because motor responses remained contingent upon visual stimuli and no motor preparation could occur. As previously proposed (Dronkers, 1996; Kennerley et al., 2004; Tanji, 2001), this result confirms that both regions are more specifically involved in planning and implementing the temporal execution of movements underlying ongoing action chunks.

Our findings may explain the involvement of BCA regions in a variety of behavior, including working memory which involves rehearsal and hierarchical reorganization of mental representations of action in memory (Bor et al., 2003), task-sequence learning (Koechlin et al., 2002), and task-set switching (Dove et al., 2000; Konishi et al., 1998; Rogers et al., 1998). These behaviors are

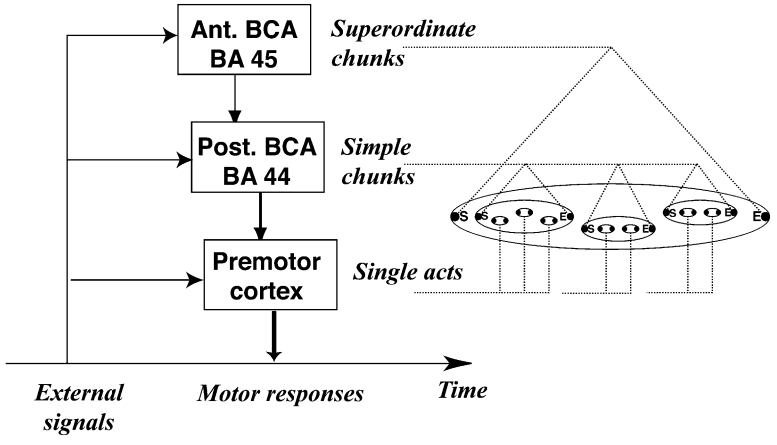

Figure 7. The Proposed Model of Hierarchical Control in BCA Regions

Left, functional organization of BCA regions. Right, schematic diagram representing how this functional organization is involved in hierarchical control based on processing start (S) and end (E) states of functional segments forming the hierarchical structure of action plans.

based on chunking action into nested functional segments, including simple and superordinate chunk-like sequences of motor acts, sensorimotor mappings, or sequences of sensorimotor mappings. BCA activations have also been reported when humans reproduce or passively observe movement sequences performed by others (e.g., Grezes et al., 2003; Iacoboni et al., 1999). This finding further suggests that the system of hierarchical control we describe is involved in identifying action plans performed by others from their perceived movements, i.e., by identifying start and end states as well as the nesting of functional segments in sequences of observed movements.

We found that activations associated with selection of functional segments into structured action plans were confined to the posterior portion of the lateral prefrontal cortex. The functional segments were selected either in response to immediate external signals, possibly through hierarchical control, or as immediate successors of previously executed segments. Moreover, the associated lateral prefrontal activations were only phasic. This result confirms the view that the posterior portion of the lateral prefrontal cortex is involved in action selection relevant to its immediate context, a function corresponding to the lowest level of the prefrontal executive system that governs the temporal organization of behavior (Braver et al., 2003; Fuster, 1989; Koechlin et al., 1999, 2003; Sakai et al., 2002). In contrast, more anterior prefrontal regions (areas BA 46 and 10) implement higher stages of executive control over time showing sustained activation related to action selection based on integrating information from temporally dispersed events (Braver et al., 2003; Fuster, 1989; Koechlin et al., 1999, 2003; Sakai et al., 2002). Consistently, we found no sustained activation in anterior prefrontal regions during simple and superordinate chunk compared to baseline trials, because in baseline and chunk conditions, information conveyed by external signals and required for action selection was equally distributed over time. Finally, it is worth noting that the same anterior prefrontal regions (i.e., BA 46) are contiguous with anterior BCA regions (i.e., BA 45) engaged in processing superordinate action chunks. Thus, the level of superordinate chunking seems to represent the apex of the prefrontal system controlling the hierarchical organization of behavior. A theoretical argument also supports this hypothesis: two nested, abstract levels of chunking (i.e., simple versus superordinate) appear sufficient to generate/process complex structures with multiple hierarchical levels, provided that lower-level representations are recursively remapped onto higher-level representations through reciprocal interactions.

In conclusion, our results provide evidence that Broca's area and its right homolog implement a specialized executive system controlling the selection and nesting of action segments comprising the hierarchical structure of behavioral plans, regardless of their temporal structure. This finding suggests a basic segregation between prefrontal executive systems involved in the hierarchical and temporal organization of goal-directed behaviors, highlighting the specific contribution of Broca's area and its right homolog to executive control. Interestingly, Broca's area is mostly known to be critically involved in human language (e.g., Martin, 2003), especially in processing hierarchical structures of human language (Musso et al., 2003) and in organizing linguistic segments that compose speech (Gelfand and Bookheimer, 2003; Indefrey and Levelt, 2004). More specifically, Broca's area has been recently proposed to play a pivotal role in chunking linguistic subordinate elements into superordinate representational structures within the phonological, syntactic, and semantic dimensions of language (Hagoort, 2005). Clearly, these accounts of the role of Broca's area in language appear compatible with the system of hierarchical control we propose. Language studies also reveal that in Broca's area posterior regions (i.e., BA 44/BA6) are preferentially engaged in language tasks based on phonological processing, whereas anterior regions (i.e., BA 45/BA 44) and anterior-ventral regions (i.e., BA 47/BA 45) are more specifically involved in tasks based on syntactic and semantic processing, respectively (review in Bookheimer [2002]; e.g., Gough et al., 2005). Given that syntactic and semantic processing involve hierarchically higher linguistic representations (i.e., words and multiword utterances) than those involved in phonological processing (phonemes/syllables within words), such functional segregation in the language domain appears consistent with our findings indicating an anterior-posterior organization of Broca's area in hierarchical control. Thus, our results support the view that Broca's area implements an executive function specialized for processing hierarchical structures in multiple domains of human cognition (Thompson-Schill et al., 2005). We speculate that the modular executive system of hierarchical control we describe possibly captures key functional components that may explain the critical contribution of Broca's area to human language.

Experimental Procedures

Subjects

Subjects (right-handed, aged between 22 and 28 years) provided written informed consent approved by the French Ethics Committee (CCPPRB). The two experimental conditions were administered in separate scanning sessions on separate days. Each scanning session was preceded by a training session (see Training section below). The order of conditions was counterbalanced across subjects.

Behavioral Protocol

In the simple condition, stimuli were a single square symbol. Squares appeared in various colors: green and red were the start and stop cues, respectively. Other colors (blue and yellow) represented random distractors. Subjects repeated the same motor response to stimuli in the motor baseline (simultaneous left and right button presses—Left&Right). When a start cue occurred, they started to execute the simple action chunking trials, i.e., they followed this overlearned sequence of button presses:

$$\text{Left\&Right} \rightarrow \text{Left\&Right} \rightarrow \text{Right} \rightarrow \text{Right} \rightarrow \text{Left}.$$

The occurrence of a stop cue indicated to subjects that they were to stop this sequence and proceed with the motor baseline task again until the next start cue occurred.

In the superordinate condition, stimuli were pseudorandomly chosen letters A, B, or C. Again, letters appeared in various colors with the same color code: green and red were start and stop cues, while other colors (blue and yellow) served as random distractors. The condition included three simple chunks, i.e., letter categorization tasks, C_1, C_2, C_3 that defined three distinct sensorimotor mappings associating letters and button presses as follows:

$$C_1, A \rightarrow \text{Right}; B \rightarrow \text{Left}; C \rightarrow \text{Left}.$$

$$C_2, A \rightarrow \text{Left}; B \rightarrow \text{Right}; C \rightarrow \text{Left}.$$

$$C_3, A \rightarrow \text{Left}; B \rightarrow \text{Left}; C \rightarrow \text{Right}.$$

Subjects repeated the same categorization task C_1 in chunk baseline trial, then with the start cue they initiated a superordinate action chunk, i.e., the following sequence of categorization tasks:

$$C_1 \rightarrow C_1 \rightarrow C_2 \rightarrow C_2 \rightarrow C_3.$$

The occurrence of a stop cue indicated to subjects that they should terminate this sequence and proceed to the baseline task C_1 again until the next start cue occurred. Letters were pseudorandomly chosen so that the proportions of left and right responses were equal.

In both conditions, stop cues occurred either at the end of learned sequences (referred to as endogenous termination) or earlier (exogenous termination). Occurrences of start and stop cues were pseudorandomized so that stop cues occurred either four trials (endogenous termination), or three, two, or one trials (exogenous termination) after start cues with the following proportions: 49%, 17%, 17%, and 17%, respectively. Similarly, and with the same proportions, start cues occurred either four, three, two, or one trials after stop cues. Thus, baseline tasks included either four, three, two, or one trials.

Stimulus duration was 500 ms. Variable stimulus onset asynchronies (SOA) were used to separately compute event-related hemodynamic responses to each trial type. SOAs uniformly ranged from 2400 ms, 4800 ms, 7200 ms, to 9600 ms. Finally, to avoid possible concatenation between action chunks and baseline trials into longer chunks, stop cues were replaced by start cues in half of termination trials, indicating to subjects that they should stop and restart ongoing action chunks. Because restart, initiation, and termination trials were associated with virtually the same brain activations, restart trials were factored out in all reported analyses for clarity.

Training

A few days before each scanning session, subjects received written instructions describing the experimental condition and informally performed the task with experimenter feedback. Then, subjects were trained to overlearn action chunks by performing the tasks on four series of stimuli that were similar to those used in the scanner (six series were administrated in the scanner). The last series was always performed just before subjects were scanned. During the four training series, each chunk was executed 56 times (28 times with endogenous termination). In a previous study (Koechlin et al., 2002), we showed that learning similar simple and superordinate chunks was complete after 16 repetitions. Thus, as confirmed by behavioral results in this study (see Results), both simple and superordinate chunks were overlearned by the time subjects entered the scanner.

Data Acquisition

A 3T Brucker whole-body and RF coil scanner was used to perform a structural scan for each subject followed by 6 series of 247 functional scans (TR 2000 ms, TE 35 ms, FOV 192 × 192 mm^2, acquisition matrix 64 × 64, flip angle 78°, 24 interleaved and jointed slices, voxel size 3 mm × 3 mm × 5 mm). Note that SOAs were not multiples of time of repetition, in order to maximize temporal sampling of event-related hemodynamic responses. The 6 series contained 84 chunks (42 with endogenous terminations). The experimental protocol was administered using Labview software. fMRI data were processed using SPM99 software (http://www.fil.ion.ucl.ac.uk/spm/) with standard interslice temporal rephasing, spatial realignment, linear normalization to the stereotaxic Talairach atlas (Hôpital La Timone—Marseille template; Talairach and Tournoux, 1988), spatial (isotropic 3D Gaussian kernel, 10 mm), and temporal smoothing (Gaussian kernel, 4000 ms). Although temporal smoothing decreases temporal resolution, temporal smoothing is standard in order to subsequently control for the effects of possible spurious correlations between successive fMRI scans on significance values and statistical thresholds.

Computation of Brain Activations

Statistical parametric maps were computed from local fMRI signals using a linear multiple regression model including three sets of regressors. (1) Event-related regressors were Dirac functions convolved with the canonical hemodynamic response function. In both conditions, the regressors separately modeled baseline, initiation, intermediate, endogenous, and exogenous termination and error trials. (2) Epoch-related regressors were variable-length box-car functions convolved with the canonical hemodynamic response function, separately modeling sustained effects in continuous series of baseline, simple, and superordinate trials delimited by start and stop cues. (3) Scan-related regressors modeling scanning series and signal drifts included constant, linear, and quadratic functions. As in previous studies (Koechlin et al., 2002; Koechlin et al., 2003), brain activations were first identified using a fixed-effect model assessing the fit between the multiple regression model described above and time courses of local BOLD-related magnetic resonance signals (voxel-wise threshold—$Z > 4.3$, $p < 0.05$ corrected for multiple comparisons; extent threshold—$p < 0.05$, 832 mm^3). Then, in order to account for between-subject variability and to allow inferences at the population level, regional activations identified were assessed using a random-effects model (voxel-wise threshold—$p < 0.05$ corrected for multiple comparisons over the search volumes). Note that a volume-of-interest approach using direct random-effect analyses provides virtually the same results (significance voxel-wise threshold $p < 0.005$, uncorrected).

Activations associated with initiation and termination of simple and superordinate chunks were separately computed as larger activations in both initiation and termination than intermediate trials in simple and superordinate condition, respectively. Activations associated with transitions between motor acts comprising simple chunks and between simple chunks comprising superordinate chunks were separately computed as larger activations in intermediate than baseline trials in the simple and superordinate condition, respectively. Regions jointly activated in initiation/termination of simple chunks and in transitions between simple chunks comprising superordinate chunks (yellow regions in Figure 3) were computed by masking each region related to one effect with the other effect (using an uncorrected voxel-wise threshold—$Z > 3.09$, $p < 0.001$). Localization of such activations in BCA regions was assessed using the Talairach atlas (Talairach and Tournoux, 1988) and cytoarchitectonic maximum probability maps of Brodman's area 6, 44, 45 (Amunts et al., 1999) provided in the SPM toolbox described in Eickhoff et al. (2005) (see Figure S3 and Table S1).

Regions exhibiting sustained effects in the simple and superordinate condition were separately computed as larger sustained activations during simple and superordinate chunk trials than during motor and chunk baseline trials, respectively. Given the statistical thresholds described above, these two epoch-related (sustained) contrasts revealed activations in the inferior parietal cortex only. However, in both the insula and pre-SMA, sustained effects were observed in the simple condition only, provided that in the fixed-effects model, the voxel-wise statistical threshold was lowered to $Z = 3.09$ ($p < 0.001$, uncorrected).

Analyses of Variances

We computed the mean event-related hemodynamic response (mER-HRs) in each trial type and region identified above from the peristimulus fMRI signal recorded in each voxel. First, we subtracted the estimated contribution of other events based on parameter estimates of the multiple linear regression model; then we averaged the resulting responses over each activation cluster. Peaks of mER-HRs (i.e., maximal signal changes) in premotor, posterior, and anterior BCA regions were then entered into separate repeated-measure ANOVAs with hemispheres, conditions, and trial-types as within-subject factors.

In a first ANOVA, the trial-type factor contrasted initiation/termination versus intermediate trials for assessing effects of boundaries. In a second and third ANOVA, the trial-type factor contrasted initiation versus termination and endogenous versus exogenous termination trials, respectively. Finally, in a fourth ANOVA, the trial-type factor contrasted intermediate versus baseline trials to assess the effects of transitions.

Additionally, three crossregional repeated-measure ANOVAs were performed. First, peaks of mER-HRs associated with initiation and termination trials were entered in an ANOVA including hemispheres, regions (anterior versus posterior BCA), conditions (simple

versus superordinate), and trial-types (initiation versus termination) as within-subject factors. Second, peaks of mER-HRs associated with intermediate and baseline trials in the superordinate condition were entered in an ANOVA including hemispheres, regions (anterior versus posterior BCA), and trial-types (intermediate versus baseline trials) as within-subject factors. Third, the same ANOVA was also performed for the simple condition with the region factor contrasting posterior BCA and premotor regions.

Supplemental Data

Supplemental Data for this article can be found online at http://www.neuron.org/cgi/content/full/50/6/963/DC1/.

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